# Numerical Studies of Acoustic Propagation in Shallow Water

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## LONG-TERM GOALS

To develop "exact" numerical methods and visualization techniques for the study of propagation of acoustic energy in shallow water in the time domain. Exact in this contexts means the methods place no restrictions on the underlying physics of the environment.

## OBJECTIVES

To develop new, and enhance existing, numerical methods; to establish the accuracy, robustness, flexibility, and tractability of these methods; and to apply these methods to meaningful practical problems. To create a robust software suite for the application of the methods and to develop techniques for visualizing the propagation of scalar and vector fields in complex environments.

## APPROACH

We have focused our attention on the development and use of finite-difference time-domain (FDTD) methods. These time-domain techniques, which are flexible, robust, and generally simple to implement, have previously been used by the electromagnetics community to solve a wide range of problems. We have established the accuracy of our proposed acoustic FDTD techniques by comparing to canonical problems which permit an exact solution or to results obtained using other numerical methods. The FDTD method is computationally intensive and, hence, to increase the ease with which FDTD can be applied to large problems, we are developing well-written, well-documented code to which incorporates the Parallel Virtual Machine paradigm to permit the solution of a problem using a cluster of workstations.

## WORK COMPLETED

Fundamental aspects of material boundaries in FDTD models were studied and quantified; inherent properties and artifacts of the FDTD grid were rigorously explained; FDTD algorithms were developed; the corresponding computer programs were written; and information was disseminated via journal publications, conference presentations, and the Web.

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**14. ABSTRACT**
**To develop exact numerical methods and visualization techniques for the study of propagation of acoustic energy in shallow water in the time domain. Exact in this contexts means the methods place no restrictions on the underlying physics of the environment.**

**15. SUBJECT TERMS**

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**RESULTS**

The FDTD method is obtained by discretizing the differential equations that govern the underlying system. Using a Cartesian grid, the method provides an exceedingly simple way in which to express future fields (i.e., unknown fields) in terms of past fields (known fields). For propagation in a homogeneous region, the traditional FDTD method is accurate to second-order—doubling the number of grid points per wavelength reduces inherent numerical errors by a factor of four. However, the behavior and accuracy of fields at material interfaces is much more complicated. We have derived exact expressions for the transmission and reflection coefficients for fields normally and obliquely incident on planar boundaries. Interestingly, it was found that the accuracy of the reflection and transmission coefficients is a function of the discretization used on either side of the boundary. Thus, although one may be interested only in the fields on one side of a boundary, a sufficiently fine discretization must be used on the other side to ensure that the reflection coefficient is accurate enough to prevent corruption of the fields in the region of interest. This work was reported at the 2000 IEEE AP-S International Symposium and URSI Radio Science Meeting [1].

In addition to our analysis of homogeneous plane wave interaction with material boundaries, we also studied the propagation of inhomogeneous plane waves in the FDTD grid. Inhomogeneous plane waves are important because they are required to form a complete basis set with which any field can be described. We derived the dispersion relation for inhomogeneous waves and showed that, in a lossless material, planes of constant phase are not necessarily orthogonal to planes of constant amplitude (as they must be in the continuous world). We showed how one could use the dispersion relation to determine exactly the behavior of evanescent fields in the FDTD grid when a wave is incident beyond the critical angle at a planar interface. We also firmly established several other characteristics of discretized worlds such as the inherent "grid velocity" (which is similar to Brillouin radiation in the continuous world). This work was published in *IEEE Transactions on Microwave Theory and Techniques* [2].

Previously we firmly established the ability of the FDTD method to model accurately scattering from randomly rough pressure-release surfaces. We have also made significant progress in establishing the use of FDTD methods for penetrable rough surfaces as described in a paper which appeared in *IEEE Journal of Oceanic Engineering* [3]. This work compares results obtained using the FDTD method and the method of moments. Though both methods have inherent numerical inaccuracies, their inaccuracies are independent such that when the results obtained by the two methods agree one can be confident of having obtained convergence to the correct solution. Scattering from both individual surfaces and collections of surfaces (i.e., Monte Carlo simulations) were studied and in all cases the FDTD method and the method of moment results showed good agreement.

We have developed a new FDTD scheme for the modeling of continuously varying rigid boundaries. This new scheme uses a locally conformal approach so that the usual FDTD update equations apply everywhere away from the boundary. For points adjacent to the boundary, modified equations are used. This scheme is "low cost" since the coefficients used in the modified update equations can be calculated in a preprocessing stage. We have shown that this scheme significantly improves the accuracy over that obtained using a traditional stair-step representation of the boundary. This work was reported at the December 2000 ASA Meeting [4] and is described in a paper which was submitted to the *Journal of the*

*Acoustical Society of America* [5].

We have explored several new implementations of the FDTD method (proposed by others) which seek to minimize dispersive and anisotropic errors inherent in all 2- and 3-D FDTD schemes. We have developed comparisons that provide insights into the techniques that are not easily garnered from the publications that originally presented them. This work has been submitted to *IEEE Transactions on Microwave Theory and Techniques* [6]. Along these same lines, we have adapted a variation of the promising FDTD scheme proposed by Eric Forgy (IEEE Antennas and Propagation Society International Symposium, Orlando, FL, vol. 2, 1316-1319, July, 1999) for acoustic problems. This algorithm suffers much less grid dispersion and anisotropy than more traditional FDTD formulations. This work will be described in a future publication.

We continue to maintain a Web site, `www.fdtd.org`, that seeks to list all archival publications related to the FDTD method. This site solicits input, in the form of comments posted about work appearing in the archival literature, from the entire community interested in the FDTD method (whether applied to acoustics, electromagnetics, or solid mechanics).

Our investigations of the discretized worlds of FDTD methods have led us to a better understanding of numeric artifacts associated with resonances and to ways of alleviating these artifacts. Part of this work was presented as an invited talk in a special session organized by Prof. Allen Taflove (one of the co-founders of the FDTD method) [7]. This work is further described in a paper submitted to *IEEE Transactions on Antennas and Propagation* [8]. Additionally, we have codified some of the intrinsic properties of FDTD grids that has implications for the ways in which sources should be implemented [9].

Finally, we continue to develop code that is suitable for distribution to others (e.g., modularized, re-usable, and well documented). Currently our focus is on the construction of code that can be run on a cluster of workstations using the Parallel Virtual Machine (PVM) suite of routines. The FDTD method, though straightforward, is computationally expensive and the ability to run simulations on a cluster of workstations greatly expands the the size of the problems it can address. Though the concepts behind PVM-based code are simple, the implementation details can be cumbersome and thus researchers often shy away from writing such code. By providing this code we hope to generate more interest in applying FDTD to meaningful problems as well as to entice others to aid in the development of future code. Our current visualization code, which is compatible with the output of the PVM-base code, employs the OpenGL graphics library to render the fields.

**IMPACT/APPLICATIONS**

Accurate and flexible numerical methods allow researchers to conduct any number of experiments without having to resort to actual field experiments, i.e., the experiment is conducted on the computer. Although numerical methods will never supplant field experiments, numerical methods (when used within their "region of validity") do provide an extremely cost-effective means of conducting controlled experiments. Our works enable more accurate and more efficient numerical solutions to a wide range of problems in acoustics, electromagnetics, and continuum mechanics.

**TRANSITIONS**

Much of the knowledge we have gained has been disseminated via publications and conference presentations. Additional material is available via the Web. Please refer to the Web site given in the header for copies of the PI's publications or `www.fdtd.org` for other material pertinent to the FDTD method.

**RELATED PROJECTS**

This work is related to research in both high-frequency acoustics and long-range propagation. Numerical models, such as the FDTD method, can be used to predict the fields scattered from small objects under short-wavelength insonification or the propagation of long-wavelength signals over limited regions of the ocean. Additionally, this work is related to several other ONR-sponsored researchers including Shira Broschat, Eric Thorsos, Philip Marston, and Ralph Stephen.

**PUBLICATIONS:**

[1] J. B. Schneider and R. J. Kruhlak, "Plane Waves and Planar Boundaries in FDTD Simulations," IEEE AP-S International Symposium and URSI Radio Science Meeting, Salt Lake City, UT, Jul. 2000.

[2] J. B. Schneider and R. J. Kruhlak, "Dispersion of Homogeneous and Inhomogeneous Waves in the Yee Finite-Difference Time-Domain Grid," *IEEE Trans. Microwave Theory and Techniques*, vol. 49, no. 2, pp. 280–287, 2001.

[3] F. D. Hastings, J. B. Schneider, S. L. Broschat, and E. I. Thorsos, "An FDTD Method for Analysis of Scattering from Rough Fluid-Fluid Interfaces," *IEEE Journal of Oceanic Engineering*, vol. 26, no. 1, pp. 94–101, 2001.

[4] J. B. Schneider and J. G. Tolan, "A Locally Conformal Method for Modelling Rigid Boundaries in the FDTD Method," *J. Acoust. Soc. Am.*, vol. 108, no. 5, pt. 2, pp. 2563, Newport Beach, CA, Dec. 2000.

[5] J. G. Tolan and J. B. Schneider, "Locally Conformal Method for Acoustic Finite-Difference Time-Domain Modeling of Rigid Surfaces," submitted to *J. Acoust. Soc. Am.*

[6] K. L. Shlager and J. B. Schneider, "Comparison of the Dispersion Properties of Several Low-Dispersion Finite-Difference Time-Domain Algorithms," submitted to *IEEE Trans. Antennas Propagat.*

[7] C. L. Wagner and J. B. Schneider, "Using the Dispersion Relation to Understand Finite-Difference Time-Domain Worlds," International Conference on Electromagnetics in Advanced Applications (ICEAA 01), Torino, Italy, pp. 375–378, Sep. 2001.

[8] C. L. Wagner and J. B. Schneider, "On the Analysis of Resonators Using Finite-Difference Time-Domain Techniques," submitted to *IEEE Trans. Antennas Propagat.*

[9] C. L. Wagner and J. B. Schneider, §5.4, "$\vec{J}$ and $\vec{H}$ Current Sources in Three Dimensions," in *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, 2 ed., Allen Taflove and Susan Hagness, Artech House, Boston, MA, 2000.